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基于FLUXNET的CLM模型生态系统呼吸模拟验证*

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摘 要 准确估算陆地生态系统呼吸(Ecosystem respiration, RE)对全球陆地生态系统碳收支研究具有重要意义. 模型模拟是估算陆地RE变化的一种常用手段. 然而目前陆地生态系统过程模型的RE模拟尚未得到充分验证. 基于耦合模式比较计划第五阶段(Coupled Model Intercomparison Project Phase 5, CMIP5)的通用陆面模型(Community land model, CLM)RE模拟结果和全球通量网(FLUXNET)66个站点的涡度相关通量观测数据(277条站点年数据)评估CLM模型对RE的模拟效果. 结果表明:(1)在空间尺度上, CLM低估了高纬度站点RE, 高估了低纬度站点RE, 但高纬度低估量更大导致空间格局整体低估(相对误差为−3.56%).(2)在时间尺度上, CLM模型基本捕捉了RE的年际和季节变化, 相关系数分别为0.60($P < 0.001$)和0.63($P < 0.001$); CLM低估年尺度和月尺度的RE(以C计), 绝对误差分别是−182.21 g m^{-2} a^{-1}、−120.16 g m^{-2} mon^{-1}, 相对误差分别是−17.84%、−10.60%.(3)CLM模型对不同植被功能型的RE模拟效果不同, 由优及差依次为混交林、常绿针叶林、草地、农田、落叶阔叶林、常绿阔叶林. 本研究在时空尺度上量化了CLM模型的生态系统呼吸模拟误差, 并分析了土壤呼吸Q_{10}和MR_{base}参数以及土壤碳库模拟等因素的影响, 可为CLM模型的生态系统呼吸模块参数优化提供依据, 进而提升其模拟精度.(图4 表3 参80 附图2 附表2)

关键词 生态系统呼吸; 通用陆面模型(CLM); 全球通量网(FLUXNET); 模拟效果
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Benchmarking the ecosystem respiration simulated by CLM based on FLUXNET*

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Abstract Accurate estimation of terrestrial ecosystem respiration (RE) is of great significance to the study of the global terrestrial ecosystem's carbon budget. Model simulation is a common method to simulate terrestrial RE changes. However, the RE simulation of the current terrestrial ecosystem's process models has not been fully verified yet. In this study, we evaluated the RE simulated by the Community Land Model (CLM) using eddy covariance flux observations of 66 stations from FLUXNET (277 site-years). The results showed that: (1) CLM underestimated RE at high latitude sites while overestimated it at low latitude stations. The magnitude of the former was larger than that of the latter, thus leading to the overall underestimation of RE (the relative error was −3.56%). (2) At the temporal scale, CLM roughly captured the interannual and seasonal variation

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of RE. The correlation coefficients were 0.60 ($P < 0.001$) and 0.63 ($P < 0.001$), respectively. CLM underestimated the annual and monthly RE, with the absolute error of 182.21 g C m^{-2} a^{-1} and 120.16 g C m^{-2} mon^{-1}, respectively. The relative errors were 17.84% and 10.60%, respectively. (3) The simulation results of the different plant functional types from the best to worst were ranked as mixed forest, evergreen coniferous forest, grassland, farmland, deciduous broadleaved forest, and evergreen broadleaved forest. This study quantified the error of CLM-RE simulation at the spatial-temporal scale and analyzed its influence factors, such as soil respiration Q_{10}, MR_{base} parameters, and soil carbon reservoir simulation. The results can help in optimizing CLM-RE and improving the accuracy of RE simulations.

Keywords ecosystem respiration; Community Land Model (CLM); FLUXNET; simulated performance

陆地生态系统呼吸（Ecosystem respiration, RE）和总初级生产力（Gross primary productivity, GPP）共同决定陆地生态系统净碳交换量（Net ecosystem exchange of CO_2, NEE）的大小. 因此，准确量化RE和GPP的动态趋势对理解陆地生态系统碳汇变化至关重要[1]. 然而，RE受复杂的物理、化学和生物相互作用过程的调控，具有很强的时空异质性，在全球尺度上尚未被准确估算[2]，从而给全球陆地生态系统碳收支评估带来较大不确定性. Ballantyne等研究表明在气候变化背景下，增温减缓导致的RE降低成为陆地生态系统碳汇增加的主要原因[3]. 因此准确估算陆地RE对全球陆地生态系统碳收支研究具有重要意义.

近年来，RE模拟验证多集中于森林[4-6]、草地[7-8]和农田[9]等单一生态系统，对不同生态系统类型综合验证分析相对较少. 同时，RE模拟验证研究范围多侧重于某一地区或大洲，例如北美[10]、欧洲[11]和东亚[12]等区域，而全球尺度上的验证研究相对欠缺. RE的估算主要包括遥感模型[2, 13]和过程模型[14-16]，其中遥感模型结构相对简单，难以表达较完整的RE机理过程[17]，所以RE模拟不确定性仍较大. 过程模型其相对完善的参数化结构可较精确地模拟RE变化过程[18]. 通用陆面模型（Community Land Model, CLM）包含植被、凋落物、土壤碳氮和植被物候等模块，是模拟大气–植被–土壤连续生物地球物理和生物地球化学过程的主流模型[19]. 同时，CLM可较精确地模拟不同尺度不同植被型的GPP、蒸散（Evapotranspiration, ET）[20-23]和叶面积指数（Leaf Area Index, LAI）[24-25]等变量，但在全球尺度上的RE模拟结果尚未验证.

涡度相关技术的通量观测是直接测定陆地生态系统与大气间碳水通量的重要方法，为全球陆地生态系统碳循环过程及其控制机理、时空格局等方面的研究提供了重要信息[26]. 目前全球FLUXNET通量长期监测网络经27年发展为准确估算碳通量变化提供了良好的平台[27]. 本研究利用FLUXNET-66个站点（覆盖全球21个国家）的RE观测数据对CLM-RE模拟结果进行验证，包括常绿阔叶林（EBF）、落叶阔叶林（DBF）、常绿针叶林（ENF）、混交林（MF）、草地（GRA）、农田（CRO）6种不同植被功能型（按国际地圈生物圈计划（International Geosphere Biosphere Programme, IGBP）分类），从空间格局、年际和季节变化对CLM-RE模拟结果进行验证分析，旨在评估此模型对不同生态系统的适用性及预测精度，并探究模拟的主要误差和不确定性来源，为后续CLM呼吸模块参数改进提供依据，进而提高CLM-RE模拟精度，为全球陆地生态系统碳收支研究提供支撑.

1 数据与方法

1.1 FLUXNET-RE观测数据

FLUXNET作为全球涡度相关通量观测网络，是目前最大的CO_2、H_2O和能量通量的合成数据集（http://fluxnet.fluxdata.org/），其共享的通量数据经过统一质量控制、插补和拆分处理[28-29]，将NEE拆分出RE和GPP供科学工作者研究应用. 本文将拆分的RE数据作为观测数据用以CLM-RE模拟结果的验证分析，并在原有数据处理的基础上进一步作了异常值识别和剔除，最终选取的66个站点（277站点年数据）分布于热带、温带和寒带. FLUXNET-RE观测数据时间范围从1999-2005年不等，1-3年共28个站点，4-6年共25个站点，7年以上共13个站点，欧洲和亚洲通量站点数据累计较多. 66个站点共包含混交林、草地、常绿阔叶林、常绿针叶林、落叶阔叶林和农田6种植被功能型，详细站点信息参见附表1.

1.2 CLM_RE模拟数据

CMIP5是世界气候研究计划（World Climate Research Programme, WCRP）耦合模型工作组（Working Group on Coupled Modelling, WGCM）和国际地圈–生物圈计划（International Geosphere_Biosphere Programme, IGBP）共同推出协调气候的模型试验计划[30]，超过20个气候模式组的50多个模式对历史和未来全球气候进行了数值模拟试验. CESM1是模拟地球气候系统的耦合气候模式，是CMIP5众多模式之一，可模拟地球大气层、海洋、陆地、陆地冰和海冰等不同过程，其中CLM是CESM1的陆面部分. CLM是NCAR（National Center of Atmospheric research）发展推广的陆面过程模型，它在综合BATS（Biosphere-Atmosphere Transfer Scheme, BATS）、IAP94（Land surface model which was established at the Institute of Atmosphere Physics, Chinses Academy of Sciences in 1994, IAP94）、LSM（Land Surface Model, LSM）等陆面模型优点的基础上，改进了一些物理过程参数化方案，并且加入水文、动态植被等过程[19]，是目前世界上发展较为完善且具发展潜力的陆面过程模型之一. 本文的RE模拟数据来源于CLM模型的历史模拟数据（https://esgf-node.llnl.gov/search/cmip5/），时间覆盖范围为1850-2005

年. 此外, 本文在原有下载数据的基础上进行了投影转换, 并利用66个FLUXNET站点的经纬度在0.9° × 1.25°的空间尺度上提取了对应的RE模拟数据且作了异常值筛选, 同时也按照IGBP分类对CLM-RE模拟数据进行了划分, 其数据年份选择和时间尺度划分处理方法与观测数据相同.

1.3 CLM-RE模拟结构

CLM模型模拟生态系统呼吸可分为自养呼吸(Autotrophic respiration, RA)和异养呼吸(Heterotrophic respiration, RH), 其中自养呼吸包括用于新组织合成的生长呼吸(Growth respiration, RG)和已合成的活组织(叶、细根、活粗根、活枝干)在维持功能状态过程中的维持呼吸(Maintenance respiration, RM), 而异养呼吸主要是土壤呼吸中的微生物呼吸. 自养呼吸是氮含量、基础维持呼吸速率和温度的函数, 异养呼吸是土壤碳含量、碳库周转速率、温度和湿度的函数[19], 其表达式如下:

$$RG = 0.3 \times CF_{alloc} \quad (1)$$

$$RM = NS \times MR_{base} \times Q_{10RA}{}^{(T-T_{ref})/10} \quad (2)$$

$$RH = C \times K \times T_{\_scalor} \times W_{\_scalor} \quad (3)$$

$$T_{\_scalor} = Q_{10RH}{}^{(T-T_{ref}*)/10} \quad (4)$$

$$W_{\_scalor} = \sum_{j=1}^{5} \begin{cases} 0 & \varphi_j < \varphi_{min} \\ \dfrac{\log(\phi_{min}/\phi_j)}{\log(\phi_{min}/\phi_{max})}\, r_j & \varphi_{min} \le \varphi_j \le \varphi_{max} \\ 1 & \varphi_j \ge \varphi_{max} \end{cases} \quad (5)$$

$$RE = RG + RM + RH \quad (6)$$

式中, CF_{alloc}是用于植被生长光合产物, NS为植物体活组织的氮含量(N, g m^{-2}), C为土壤碳含量(C, g m^{-2}), MR_{base}=2.525e^{-6}为每单位氮的基础维持呼吸速率(C/N, gg^{-1} s^{-1}) K为土壤碳库周转速(d^{-1}), $T_{_scalor}$和$W_{_scalor_j}$分别是温度和湿度对异养呼吸的影响. Q_{10RA}和Q_{10RH}分别是自养呼吸和异养呼吸的温度敏感系数(Q_{10RA}=Q_{10RH}=1.5), T为一定条件下的空气温度和土壤温度(℃), T_{ref}和$T_{ref}{}^*$分别是自养呼吸和异养呼吸的参考温度(T_{ref} = 20 ℃, $T_{ref}{}^*$ = 25 ℃). CLM模型土壤呼吸模块为单层土壤有机质结构, 模型只考虑前五层土壤组分(29 cm), r_j为第j层土壤中根分布的比例, φ_j、φ_{min}、φ_{max}分别为第j层土壤水势, 最低土壤水势和饱和土壤水势(通过土壤质地确定).

1.4 统计方法

本研究从时空尺度对CLM-RE模拟能力进行了验证分析, 模拟结果度量指标主要包括皮尔逊相关系数(R)和均方根误差(RMSE). 另外, 季节变化除了R和RMSE, 还选取标准差(SD)和归一化后的中心均方根误差(RMSD)对模拟效果进行综合排名[10]. 具体计算步骤如下: (1) 分别对66个站点/6个植被型4项度量指标由优及差进行排序(RMSE、RMSD、SD升序; R降序), 并对排名结果按顺序赋值; (2) 计算66个站点/6个植被型4项度量指标排序结果的平均值和标准差, 并对平均值从小到大排序, 排序越小代表其模拟效果越好.

$$R = \frac{\sum_{n=1}^{N}(m_n - \overline{m})(o_n - \overline{o})}{\sqrt{\sum_{n=1}^{N}(m_n - \overline{m})^2 \sum_{n=1}^{N}(o_n - \overline{o})^2}} \quad (7)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(m_n - o_n)^2} \quad (8)$$

$$SD = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(m_n - \overline{m})^2} \quad (9)$$

$$RMSD = \sqrt{\frac{1}{N}\sum_{n=1}^{N}[(m_n - \overline{m})(o_n - \overline{o})]^2} \quad (10)$$

式中, R为相关系数, RMSE为均方根误差, SD为标准差, RMSD为中心均方根误差, m_n为第n个模拟值, o_n为第n个观测值, N为总样本数.

2 结果分析

2.1 RE空间格局模拟效果

CLM捕捉RE空间格局模拟效果相对较好(R = 0.64, P < 0.001)(图1a), 与FLUXNET观测的66个站点RE年总量(C, 1 082.46 g m^{-2} a^{-1})相比, CLM模拟RE的绝对误差为–38.43 g m^{-2} a^{-1}, 相对误差为–3.56%. 各植被型RE模拟效果有所差异(图1a), 常绿阔叶林除AU-Tum站点模拟RE低估外, 其余站点模拟RE均高估, 使得常绿阔叶林整体RE高估量占比观测值31.54%; 农田、草地和落叶阔叶林低估站点较多, 其模拟RE相对误差为–12.51%至–21.75%; 常绿针叶林和混交林高估站点占各自总站点数约40%, 其模拟RE相对误差分别是11.64%和4.09%. 不同纬度带下RE模拟效果差异相对较大(图1b), 纬度高于50°的17个站点其RE被低估, 平均低估量为374.97 g m^{-2} a^{-1}, 占比观测值–36.26%; 低纬度地区RE被高估, 特别是常绿针叶林的MY-PSO、CN-Qin和常绿阔叶林的CN-Din较明显, 高估量大于1 200 g m^{-2} a^{-1}; 而中纬度地区RE存在不同程度的高估和低估, 模拟偏差为–955.80 - 358.29 g m^{-2} a^{-1}.

2.2 RE年际变化模拟效果

CLM模拟RE年际变化相关性总体相对较高(图2), R值为0.60(P < 0.01). 落叶阔叶林、常绿针叶林和农田模拟效果相对较差, R值均小于0.3. 混交林、草地和常绿阔叶林模拟效果相对较好, R值分别是0.62(P < 0.01)、0.47(P < 0.01)和0.47, 因此CLM-RE模拟值与观测值年际变化相关性总体较高.

除常绿阔叶林模拟RE年际变化整体高估以外, 其余5种植被型模拟RE年际变化均存在不同程度的低估, 使得CLM模拟RE年际变化总体低估, 其相对误差为–10.60%(表1). 落叶阔叶林、混交林和农田模拟RE偏差相对较小(RMSE介于234.60-350.82 g m^{-2} a^{-1}), 而常绿阔叶林、常绿针叶林和草地模拟RE偏差相对较大(RMSE介于405.09-1024.24 g m^{-2} a^{-1}), 使得模型模拟RE偏差总体相对较大(RMSE = 590.94 g m^{-2} a^{-1}). 整体来看混交林相对较高的相关性及较低的模拟偏差使得模型在年际变化捕捉过程中效果相比其他植被型较好.

2.3 RE季节变化模拟效果

除常绿阔叶林观测RE为“双峰”型变化之外, 其余植被型季节特征相似, 大都表现出“单峰”型变化(图3). 另外, 除常绿阔叶林季节变化整体高估(平均高估52.62 g m^{-2} mon^{-1}, 相对误差为37.95%)之外, 其余植被型逐月均存在不同程度的高估/低估. 农田、常绿针叶林和草地冬季(12-次年

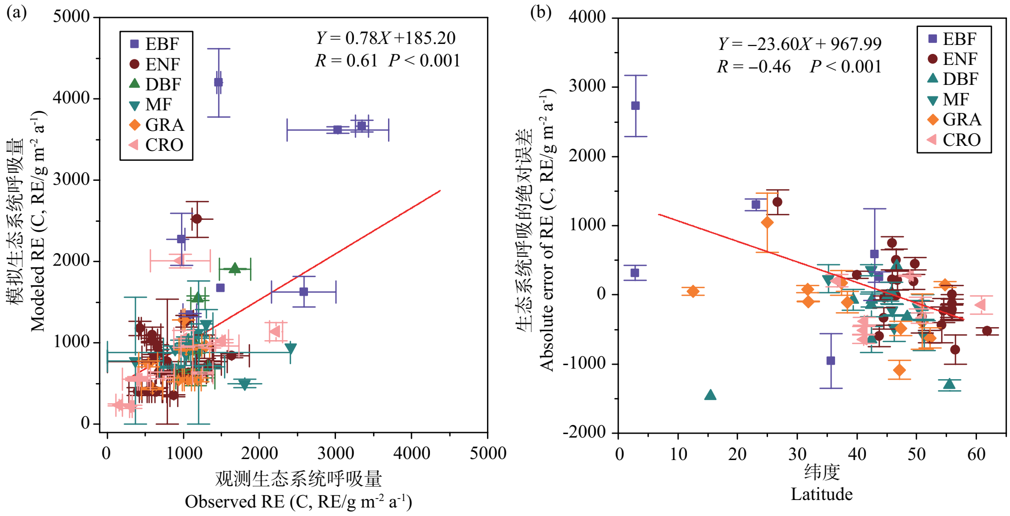

图1 各植被型RE模拟与观测空间格局对比（a）及RE绝对误差随纬度变化规律（b）. MF：混交林；GRA：草地；ENF：常绿针叶林；EBF：常绿阔叶林；DBF：落叶阔叶林；CRO：农田.

Fig. 1 Comparison of the spatial pattern of RE in different plant functional types between simulation and observation (a) and the variation of absolute error of RE with latitude (b). MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland

2月）RE高估14.73 g m^{-2} mon^{-1}，占比观测值61.03%；落叶阔叶林和混交林冬季模拟RE与观测值相对吻合，相对误差仅为7.79%. 落叶阔叶林、常绿针叶林、草地、混交林和农田生长季（4-9月）低估相对较大，平均低估47.20 g m^{-2} mon^{-1}，占比观测值35.48%；尤其农田生态系统生长旺季低估较明显，其低估量高达118.35 g m^{-2} mon^{-1}，占比观测值62.37%. 此外，CLM模型没有捕捉到常绿阔叶林RE的“双峰”型变化，且RE模拟值相比观测值逐月存在较大正偏差（RMSE = 54.14 g m^{-2} mon^{-1}）. 各站点季节变化趋势图参见附图1.

CLM模拟RE季节变化相关性较高（R = 0.63，P < 0.001），且各植被型模拟相关性均在0.5以上（图4）. 混交林模拟结果相比观测值大多位于1:1线附近，且相关系数可达0.80（P < 0.001），表明混交林RE模拟效果相比其余植被型较好. 为了进一步评估各植被型及各站点综合模拟效果，本研究根据各度量指标（R、RMSE、RMSD、SD）对其模拟效果进行综合排名，各植被型模拟效果由优及差依次为混交林、常绿针叶林、草地、农田、落叶阔叶林、常绿阔叶林，详

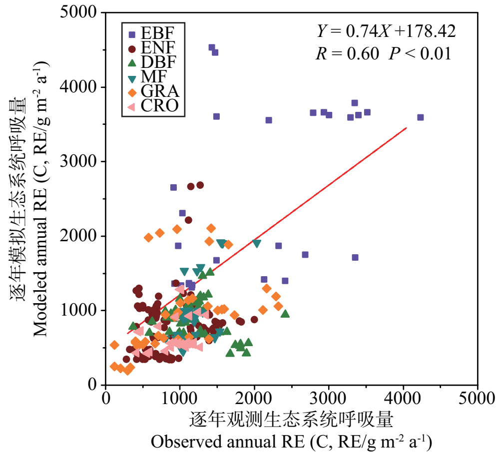

图2 各植被型RE的年际变化模拟与观测对比. MF：混交林；GRA：草地；ENF：常绿针叶林；EBF：常绿阔叶林；DBF：落叶阔叶林；CRO：农田.

Fig. 2 Comparison of the interannual variability of RE in different plant functional types between simulation and observation. MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland

表1 各植被型RE的年际变异模拟与观测评估

Table 1 Evaluation of the interannual variability of RE in different plant functional types between simulation and observation

植被功能型 Plant functional type	样本数 Sample	模拟值年均量 Annual average of simulated RE (RE/g m^{-2} a^{-1})	观测值年均量 Annual average of observed RE (RE/g m^{-2} a^{-1})	绝对误差 Absolute error (AE/g m^{-2} a^{-1})	相对误差 Relative error (P/%)	相关系数(R)	均方根误差 (RMSE/g m^{-2} a^{-1})
EBF	27	2593.87	2110.39	483.48	22.91	0.47	1024.24
ENF	102	775.00	896.69	−121.69	−13.57	0.20	405.09
DBF	32	887.16	1225.10	−337.93	−27.58	0.26	244.03
MF	50	1008.78	1216.79	−208.01	−17.10	0.62*	350.82
GRA	28	958.54	1019.53	−60.99	−5.98	0.47*	486.19
CRO	38	662.10	949.79	−287.70	−30.29	0.22	234.60
ALL	277	1013.31	1133.47	−120.16	−10.60	0.60*	590.94

*表示相关关系显著（P < 0.01）. MF：混交林；GRA：草地；ENF：常绿针叶林；EBF：常绿阔叶林；DBF：落叶阔叶林；CRO：农田.

* means significant correlation (P < 0.01). MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland.

细站点排名参见表2.

3 讨论

本研究利用FLUXNET站点RE观测数据评估的CLM时空尺度模拟RE大小以及变化捕捉情况与已有模型研究结果较为接近. 基于CASA模型估算的全球多数站点RE存在低估[31], CLM模型利用站点观测数据作为模型驱动的模拟RE（千烟洲和鼎湖山站点）存在高估[32], 这与本文RE空间格局的整体低估和低纬站点RE高估相一致. 另外, 多数陆地生物圈模型低估了北美地区RE的年际变化[10], 遥感模型和过程模型对不同植被型RE的年际和季节模拟效果均存在差异[13-14], ORCHIDEE模型高估了常绿阔叶林RE的季节变异（以法国Pue站点为例）[11]. CLM模型对长时间序列观测的哈佛森林站点（US-Ha1）的模拟效果与Urbanski等[33]的研究结

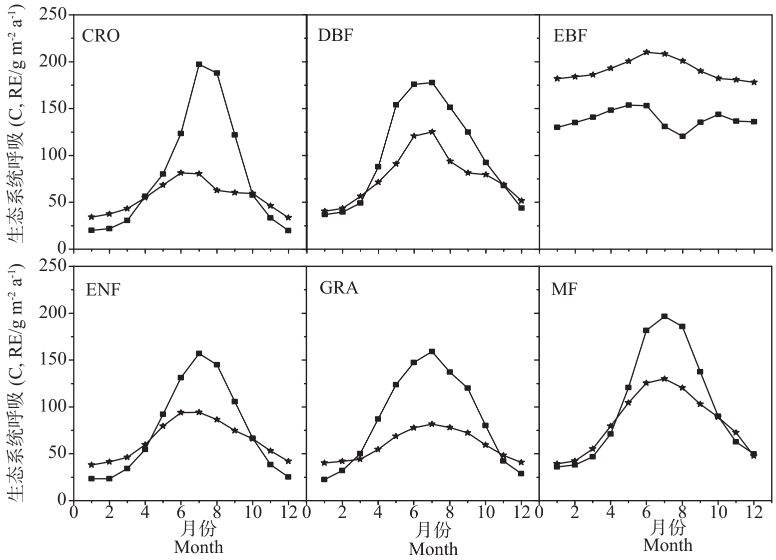

图3 各植被型RE模拟值（★）与观测值（■）的多年平均季节变化. MF: 混交林; GRA: 草地; ENF: 常绿针叶林; EBF: 常绿阔叶林; DBF: 落叶阔叶林; CRO: 农田.

Fig. 3 Mean annual seasonal variations of simulated (★) and observed (■) RE for all plant functional types. MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland

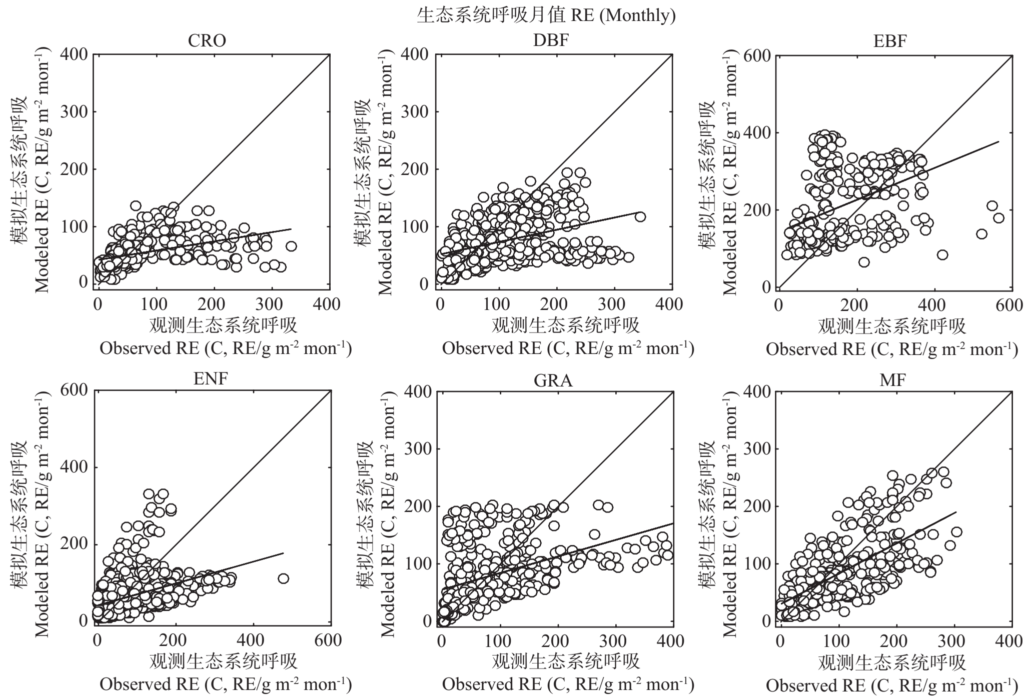

图4 各植被型月尺度RE模拟与观测值散点图. MF: 混交林; GRA: 草地; ENF: 常绿针叶林; EBF: 常绿阔叶林; DBF: 落叶阔叶林; CRO: 农田.

Fig. 4 The scatter plots of the monthly simulated and observed RE of different plant functional types. MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland

果也基本一致. 此外, 本研究将CLM-RE全球模拟结果与区域性RE模拟结果进行比较, 发现模型全球尺度RE模拟效果相比区域性RE模拟效果差异较大(表3). 其中北美和欧洲地区各植被型RE季节变化模拟相关性与全球模拟结果较为接近, R值相差0.1左右, 而东亚地区各植被型RE季节变化模拟相关性相比全球较高, 草地R值相差0.48, 这可能是模型驱动数据及空间分辨率不同所致. 欧洲地区各植被型整体RE季节变化模拟偏差相比全球、北美和东亚地区较高, RMSE介于63.90-93.00 g m^{-2} mon^{-1}, 这主要是由于模型没有考虑到欧洲地中海地区夏季土壤水限制等因素[35]. 混交林在北美、欧洲、东亚乃至全球尺度上其模拟效果相比其他植被型均较好.

FLUXNET-RE与CLM-RE的空间分辨率不匹配对模型模拟评估会造成一定的影响. CLM-RE模拟数据的空间尺度为0.9° × 1.25°, 而涡度相关通量数据空间尺度一般在1-10 km, 所以数据集空间尺度的差异会影响CLM-RE空间格局的模拟效果. 同时, 观测条件的限制导致NEE测定结果与其他方法的估计结果相差80%-200% [35], 且部分异常数据判断标准和缺失数据插补方法的选择会造成通量数据存在差异, 因此通量数据本身也存在一定的不确定性, 这种不确定性会影响CLM-RE的空间、年际和季节捕捉效果.

RE对温度的敏感性-Q_{10}是CLM模拟生态系统呼吸的关键因子, 一直以来它的大小是关注的热点[36]. 以长白山温带混交林为例的敏感性分析结果表明, 对RE影响较大的生态系统呼吸参数为土壤呼吸敏感性参数Q_{10}-RS和土壤碳库周转速率K(附表2). 这两个参数变化10%将分别引起RS变化88%和63%, 并分别使RE变化82%和60%. 可见, 土壤呼吸敏感性参数Q_{10}-RS是影响生态系统呼吸的重要参数. CLM模拟全球尺度RE的Q_{10}仅区分自养呼吸(Q_{10} = 1.5)和异养呼吸(Q_{10} = 1.5), 并无植被型和区域的划分. 而Zhou等利用模型反演算法得出全球平均土壤呼吸Q_{10}(Q_{10}-siol respiration, Q_{10}-RS)为1.72, 且各植被型Q_{10}-RS差异较大, 同时全球平均Q_{10}-RS相比区分植被型的Q_{10}-RS, 其模拟RE约低估25% [31]. 说明本研究较低的Q_{10}-RS以及无植被型区分可能是模拟RE空间尺度整体低估的部分原因. Xu等研究表明模型高纬相比低纬较高的Q_{10}-RS可降低高纬站点RS的模拟误差, 进一步表明高纬站点的Q_{10}-RS较小可能是导致其模拟RE低估的原因之一[37]. 另外, Curiel 等研究发现生长季相比非生长季较高的Q_{10}-RS可促进模型更好地捕捉季节变异, 这也可能是本研究RE模拟值在生长旺季相比观测值低估74.16%的部分原因[38]. Peng等研究发现土壤深度为0-10 cm时, Q_{10}-RS随土壤深度增加而增大, 而CLM模拟全球RE未考虑多层土壤有机质结构, 所以对RE模拟结果也会产生影响[39].

此外, 包括CLM在内的多数模型模拟不同区域RE的MR_{base}为统一值, 这对RE时空格局模拟效果也有一定影响[40-41]. Yuan等研究表明利用站点MR_{base}相比全球统一值, 其全球RE模拟与观测相关性从0.5提升至0.71, 且美国东南部亚热带森林站点的MR_{base}相比较高[42]. 这说明利用站点MR_{base}可提升RE的模拟精度, 同时也可能是US-MMS站点RE模拟低估的部分原因.

表2 各植被型及各站点RE模拟效果综合排名

Table 2 Comprehensive ranking of the simulated performance of RE for all plant functional types and different sites

植被功能型/站点名称 PFT Site	综合排名 Rank	植被功能型/站点名称 PFT Site	综合排名 Rank
MF	29.21 (13.77)	DE-Gri	32.00 (20.02)
CN-Cha	24.50 (23.46)	NL-Hor	31.25 (17.48)
BE-Vie	21.00 (7.25)	CN-HaM	29.75 (19.06)
US-PFa	26.50 (13.57)	AU-How	33.50 (15.82)
US-Syv	31.00 (12.75)	US-Wkg	35.25 (20.18)
JP-SMF	32.50 (16.16)	ZA-Kru	48.75 (12.80)
BE-Bra	39.75 (9.44)	US-Ton	40.75 (23.21)
ENF	31.16 (14.36)	CRO	32.44 (12.46)
FI-Hyy	24.00 (19.66)	FI-Jok	22.75 (7.53)
US-NR1	17.50 (21.20)	US-ARM	20.25 (17.84)
RU-fyo	28.75 (20.35)	DE-Kli	28.25 (11.71)
CA-Qfo	25.75 (21.18)	BE-Lon	27.50 (7.40)
NL-Loo	27.50 (18.12)	FR-Gri	31.25 (4.82)
IT-Lav	30.25 (20.22)	US-Ne1	44.00 (19.26)
CN-Qia	41.00 (21.12)	US-Ne3	42.50 (13.65)
IT-Ren	30.50 (13.01)	US-Ne2	43.00 (17.51)
CA-SF1	29.75 (5.58)	DBF	32.55 (18.43)
CA-NS3	25.75 (7.50)	ZM-Mon	16.50 (26.27)
CA-NS5	29.50 (3.20)	US-Wi3	35.25 (30.77)
CZ-BK1	25.25 (7.46)	US-Ha1	20.00 (19.22)
CA-SF2	37.50 (11.52)	US-WCr	25.00 (14.04)
CA-NS1	27.25 (9.86)	DK-Sor	37.00 (24.30)
US-Wi4	31.00 (16.93)	US-MMS	31.50 (11.15)
DE-Tha	36.75 (6.61)	DE-Hai	34.00 (10.42)
CA-NS4	28.00 (14.92)	IT-PT1	38.50 (6.18)
IT-La2	34.50 (4.72)	FR-Fon	39.50 (13.68)
CA-NS2	31.50 (14.04)	IT-Ro2	36.75 (22.52)
US-Me2	38.25 (22.11)	IT-Ro1	44.00 (24.16)
US-Wi0	39.25 (12.30)	EBF	50.54 (10.53)
IT-SRo	43.50 (12.22)	FR-Pue	30.00 (10.32)
US-Me1	33.75 (25.46)	CN-Din	58.50 (9.01)
GRA	31.61 (18.45)	AU-Tum	47.50 (18.57)
RU-Ha1	14.75 (18.05)	AU-Wac	42.00 (13.47)
CH-Oe1	27.25 (16.78)	BR-Sa1	54.75 (12.58)
AT-Neu	33.75 (22.53)	BR-Sa3	56.00 (9.03)
US-ARM	20.75 (17.01)	MY-PSO	65.00 (0.71)

MF: 混交林; GRA: 草地; ENF: 常绿针叶林; EBF: 常绿阔叶林; DBF: 落叶阔叶林; CRO: 农田; Rank代表各植被型及各站点模拟效果排名, 括号内表示排名结果的标准差.

PFT: Plant functional type; Sites: Site name. MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf fores; CRO: Cropland. Rank represented the simulated performance of each plant function type and station, the standard deviation of the ranking results was in the parentheses

土壤碳库为RE提供了底物, 所以碳库模拟的大小也是RE模拟是否准确的原因之一. 然而, CLM整体低估全球土壤碳库[43], 并且北美、中美以及高纬度地区土壤碳库低估相比较大[44-45], 所以CLM土壤碳库的低估可能会导致全球RE低估以及高纬度RE低估相对较大. 同时较高的土壤碳库模拟和Q_{10}-RS也可降低RE模拟的整体低估[32, 46]. 另外, CLM低估了低纬度站点(中国长白山和千烟洲)的根际碳周转时间, 进而引起RS和 RE的高估[45]. CLM模拟农田生态系统的误差相比其他植被型较大, 其原因可能归咎于模型未考虑人类活动因素的影响[47].

为了进一步改进CLM模型生态系统呼吸的模拟精度,

表3 CLM-RE全球模拟与区域模拟结果比较
Table 3 Comparison of CLM-RE between global and regional simulation results

区域 Area	驱动数据 Driving data	空间分辨率 Spatial resolution	植被型 PFT	*R*	均方根误差 (RMSE/g m^{-2} mon^{-1})	参考文献 Reference
北美 North America	CRUNCEP	2.8° × 2.8°	ENF	0.64	25.30	[10]
	CRUNCEP		DBF	0.76	39.60	[10]
	CRUNCEP		CRO	0.55	58.90	[10]
	CRUNCEP		GRA	0.38	63.70	[10]
东亚 East Asia	CRU TS3.1	0.5° × 0.5°	ENF	0.93	12.60	[11]
	CRU TS3.1		DBF	0.94	10.20	[11]
	CRU TS3.1		CRO	0.9	21.90	[11]
	CRU TS3.1		GRA	0.98	8.40	[11]
	CRU TS3.1		EBF	0.45	27.90	[11]
	CRU TS3.1		MF	0.96	16.20	[11]
欧洲 Europe	ERA-I	0.8° × 0.8°	ENF	0.66	75.30	[12]
	ERA-I		DBF	0.46	93.00	[12]
	ERA-I		CRO	0.63	69.30	[12]
	ERA-I		GRA	0.6	73.50	[12]
	ERA-I		EBF	0.63	63.90	[12]
全球 Global scale	r1i1p1	0.9° × 1.25°	ENF	0.73	53.53	本研究 This study
	r1i1p1		DBF	0.52	47.88	本研究 This study
	r1i1p1		CRO	0.75	58.96	本研究 This study
	r1i1p1		GRA	0.53	57.16	本研究 This study
	r1i1p1		EBF	0.63	99.70	本研究 This study
	r1i1p1		MF	0.8	52.22	本研究 This study

MF: 混交林; GRA: 草地; ENF: 常绿针叶林; EBF: 常绿阔叶林; DBF: 落叶阔叶林; CRO: 农田.
PFT: Plant functional type; MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland.

本研究收集了文献资料[5, 48-80]，对不同植被型的Q_{10}-RS进行了整合分析（图S2）. 结果表明各植被型Q_{10}-RS相比差异较大，Q_{10}-RS最大值与最小值相差0.91. 其中，落叶阔叶林Q_{10}-RS相比其他植被型较大（2.54），常绿阔叶林Q_{10}-RS相比其他站点较小（1.75）；落叶林Q_{10}-RS（2.54）明显大于常绿林Q_{10}-RS（1.85）. 总体来看，森林生态系统的Q_{10}-RS（2.14）最大，草地生态系统（1.86）其次，农田生态系统（1.63）最小. 后期模型优化过程中应对不同植被型赋予不同的Q_{10}-RS，从而降低CLM-RE的模拟误差，提升各植被型RE的空间、年际和季节变化的模拟精度. 同时也应将更多可能因素综合考虑到CLM-RE模拟的误差诊断中，进而提高其全球时空格局的模拟精度.

4 结论

本研究利用FLUXNET-66个站点RE观测数据对CLM-RE模拟数据在时空尺度上进行验证分析. 总体而言，CLM-RE的时空尺度模拟结果与已有研究较为接近. 然而，与FLUXNET-RE 站点观测数据相比，（1）CLM-RE在空间尺度上低估站点相对较多（占比总站点数60.61%），且模型高估了低纬度站点RE，低估了高纬度站点RE；（2）CLM模型基本捕捉了RE的年际和季节变化，相关系数分别为0.60（$P < 0.001$）和0.63（$P < 0.001$），但年际和季节变化模拟均存在低估现象（相对误差分别为−17.84%、−10.60%）. 在RE季节变化模拟过程中，模型除常绿阔叶林整体高估以外，其他植被型均在生长季低估，相比观测值平均低估35.48%；（3）CLM对不同植被型模拟效果不同，由优及差依次为混交林、常绿针叶林、草地、农田、落叶阔叶林、常绿阔叶林.

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附表1 FLUXNET研究站点概况
Table S1 Information of FLUXNET sites

站点 Site	国家 Country	植被型 PFT	经度 Longitude (α/°E)	纬度 Latitude (β/°N)	研究时段 Time	观测生态系统呼吸 Observed RE (RE/g m^{-2} a^{-1})	年均温 MAT (θ/℃)	年降水量 MAP (h/mm)
BE-Bra	比利时	MF	4.5206	51.3092	1999-2005	1157.69	9.8	750
BE-Vie	比利时	MF	5.9981	50.3051	1999-2005	1154.71	7.8	1062
CN-Cha	中国	MF	128.096	42.4025	2003-2005	1192.38	3.62	713
JP-SMF	日本	MF	137.079	35.2617	2002-2005	1678.91	/	/
US-PFa	美国	MF	269.728	45.9459	1999-2005	1139.46	4.33	823
US-Syv	美国	MF	270.652	46.242	2001-2005	1127.81	3.81	826
AT-Neu	奥地利	GRA	11.3175	47.1167	2002-2005	2220.96	6.3	852
CH-Oe1	瑞士	GRA	7.7319	47.2858	2002-2005	1507.95	9	1100
CN-HaM	中国	GRA	101.18	37.37	2002-2004	383.99	–1.7	580
DE-Gri	德国	GRA	13.5125	50.9495	2004-2005	1349.51	7.2	853
NL-Hor	荷兰	GRA	5.0713	52.2404	2004-2005	1256.04	10	800
RU-Ha1	俄罗斯	GRA	90.0022	54.7252	2002-2004	411.03	/	/
US-SRM	美国	GRA	249.134	31.8214	2004-2005	313.92	17.9	380
US-Ton	美国	GRA	239.034	38.4316	2001-2005	710.43	15.8	559
US-Wkg	美国	GRA	250.058	31.7365	2004-2005	157.57	15.64	407
AU-How	澳大利亚	GRA	131.152	–12.4943	2001-2005	1002.76	/	/
ZA-Kru	南非	GRA	31.4969	–25.0197	2000-2005	1120.23	21.9	547
CA-NS1	加拿大	ENF	261.516	55.8792	2002-2005	655.26	–2.89	500
CA-NS2	加拿大	ENF	261.475	55.9058	2001-2005	527.43	–2.88	500
CA-NS3	加拿大	ENF	261.618	55.9117	2001-2005	618.34	–2.87	502
CA-NS4	加拿大	ENF	261.618	55.9117	2002-2005	403.75	–2.87	502
CA-NS5	加拿大	ENF	261.515	55.8631	2001-2005	640.51	–2.86	500
CA-Qfo	加拿大	ENF	285.658	49.6925	2003-2005	589.22	–0.36	962
CA-SF1	加拿大	ENF	254.182	54.485	2003-2005	863.91	0.4	470
CA-SF2	加拿大	ENF	254.123	54.2539	2003-2005	1071.08	0.4	470
CN-Qia	中国	ENF	115.058	26.7414	2003-2005	1179.71	17.9	1485
CZ-BK1	捷克	ENF	18.5369	49.5021	2004-2005	684.46	6.7	1316
DE-Tha	德国	ENF	13.5669	50.9636	1999-2005	1275.82	7.7	820
FI-Hyy	芬兰	ENF	24.295	61.8475	1999-2005	878.34	3.8	709
IT-La2	意大利	ENF	11.2853	45.9542	2000-2005	1049.42	7.2	1150
IT-Lav	意大利	ENF	11.2813	45.9562	2003-2005	432.31	7.8	1281
IT-Ren	意大利	ENF	11.4337	46.5869	1999-2005	596.71	4.7	809
IT-SRo	意大利	ENF	10.2844	43.7279	1999-2005	1336.05	14.2	920
NL-Loo	荷兰	ENF	5.7436	52.1666	1999-2005	1262.99	9.8	786
RU-Fyo	俄罗斯	ENF	32.9221	56.4615	1999-2005	1634.50	3.9	711
US-Me1	美国	ENF	238.5	44.5794	2004-2005	676.58	7.88	705
US-Me2	美国	ENF	238.443	44.4523	2002-2005	968.27	6.28	523
US-NR1	美国	ENF	254.454	40.0329	1999-2005	657.39	1.5	800
US-Wi0	美国	ENF	268.919	46.6188	2002-2005	790.05	/	/
US-Wi4	美国	ENF	268.834	46.7393	2003-2005	620.05	/	/
CN-Din	中国	EBF	112.536	23.1733s	2003-2005	975.95	22.16	1473
FR-Pue	法国	EBF	3.5958	43.7414	2000-2005	1085.84	13.5	883
AU-Wac	澳大利亚	EBF	145.188	–37.4259	2005-2005	1493.21	/	/

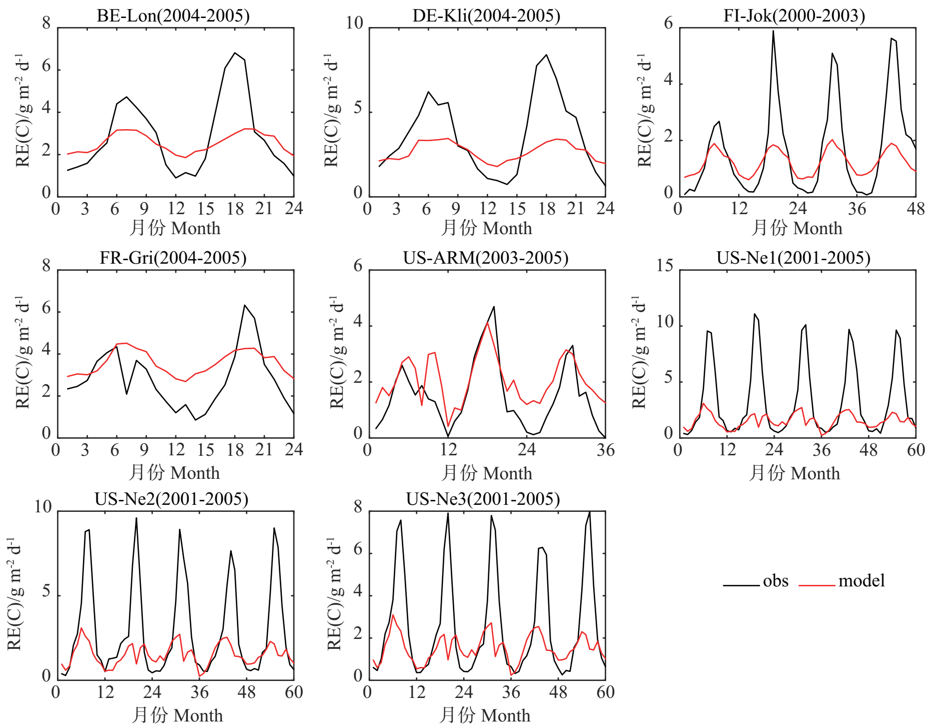
续附表1 Table S1 (Continued)

站点 Site	国家 Country	植被型 PFT	经度 Longitude (α/°E)	纬度 Latitude (β/°N)	研究时段 Time	观测生态系统呼吸 Observed RE (RE/g m^{-2} a^{-1})	年均温 MAT (θ/℃)	年降水量 MAP (h/mm)
AU-Tum	澳大利亚	EBF	148.152	–35.6566	2001-2005	2584.52	/	/
BR-Sa1	巴西	EBF	305.041	–2.8567	2002-2005	3349.45	26.13	2075
BR-Sa3	巴西	EBF	305.029	–3.018	2000-2004	3032.90	26.12	2044
MY-PSO	马来西亚	EBF	102.306	2.973	2003-2005	1465.02	/	/
DE-Hai	德国	DBF	10.453	51.0792	2000-2005	1037.61	8.3	720
DK-Sor	丹麦	DBF	11.6446	55.4859	1999-2005	1811.38	8.2	660
FR-Fon	法国	DBF	2.7801	48.4764	2005-2005	1202.43	10.2	720
IT-PT1	意大利	DBF	9.061	45.2009	2002-2004	1057.37	12.7	984
IT-Ro1	意大利	DBF	11.93	42.4081	2000-2005	1348.95	15.2	876
IT-Ro2	意大利	DBF	11.9209	42.3903	2002-2005	851.12	15.2	876
US-Ha1	美国	DBF	287.829	42.5378	1999-2005	1189.99	6.6	1071
US-MMS	美国	DBF	273.587	39.3232	1999-2005	1305.32	10.9	1032
US-WCr	美国	DBF	269.92	45.8059	1999-2005	889.29	4.02	787
US-Wi3	美国	DBF	268.901	46.6347	2004-2004	368.64	/	/
ZM-Mon	赞比亚	DBF	23.2528	–15.4378	2000-2000	2416.06	25	945
BE-Lon	比利时	CRO	4.7461	50.5516	2004-2005	1034.28	10	800
DE-Kli	德国	CRO	13.5225	50.8929	2004-2005	1296.21	9	750
FI-Jok	芬兰	CRO	23.5135	60.8986	2000-2000	591.61	4.6	627
FR-Gri	法国	CRO	1.9519	48.8442	2004-2005	1007.46	12	650
US-ARM	美国	CRO	262.511	36.6058	2003-2005	538.30	14.76	843
US-Ne1	美国	CRO	263.523	41.1651	2001-2005	1192.94	10.07	790
US-Ne2	美国	CRO	263.53	41.1649	2001-2005	1062.50	10.08	789
US-Ne3	美国	CRO	263.56	41.1797	2001-2005	931.95	10.11	784

PFT：植被功能型；MF：混交林；GRA：草地；ENF：常绿针叶林；EBF：常绿阔叶林；DBF：落叶阔叶林；CRO：农田；Observed RE：观测生态系统呼吸；MAT：年均温；MAP：年降水量；“/”：无数据.

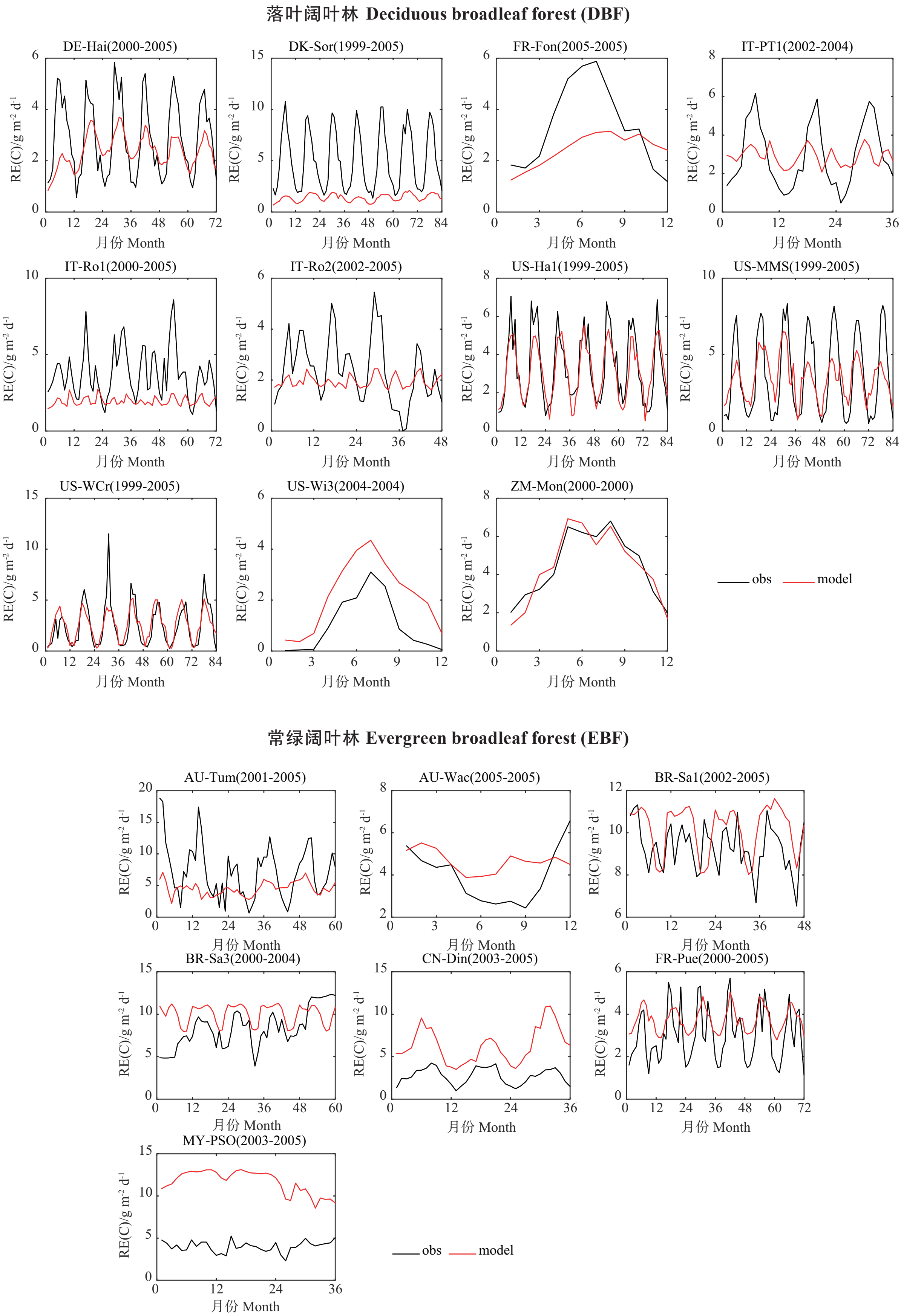
PFT: Plant functional type; MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland; Observed RE: Observed ecosystem respiration; MAT: Mean annual temperature; MAP: Mean annual precipitation; “/”: No data

农田 Cropland (CRO)



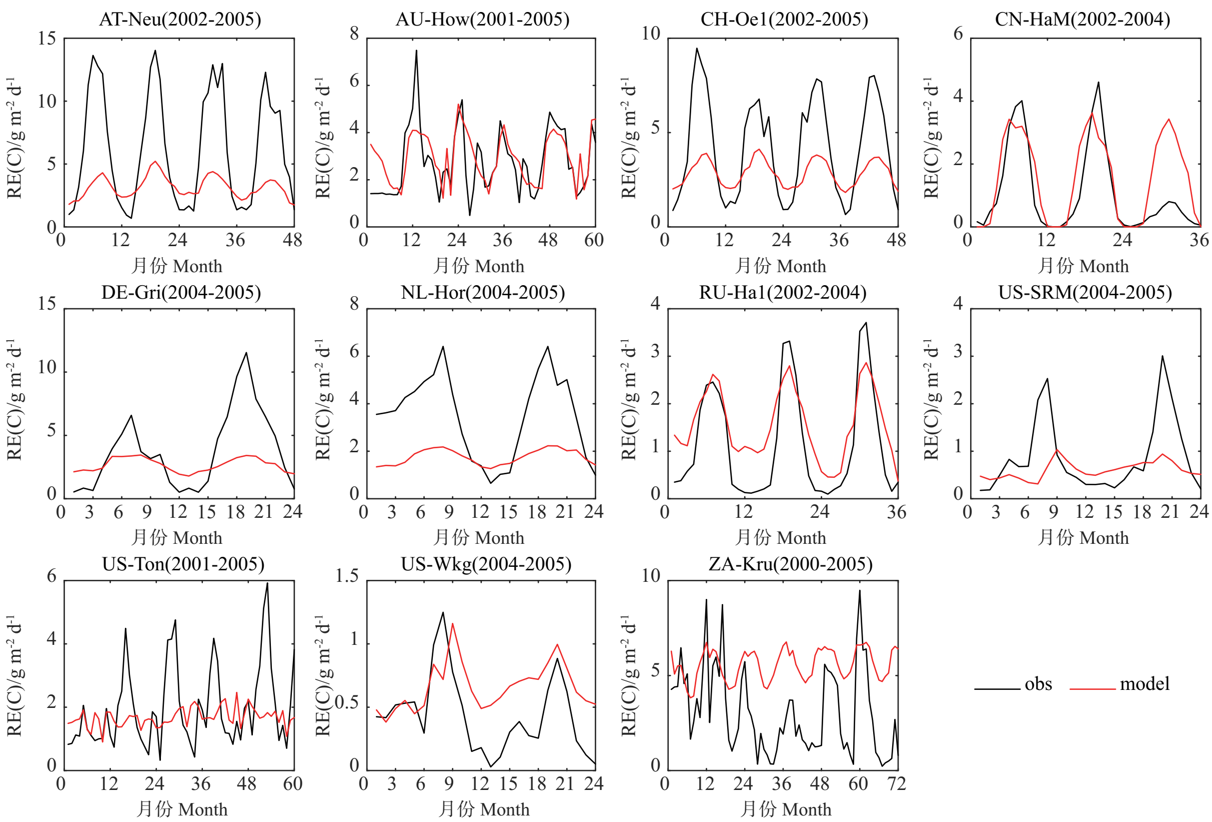
附图1 各植被型RE季节变异模拟效果.

Fig. S1 The seasonal simulation performance of RE for all plant functional types.

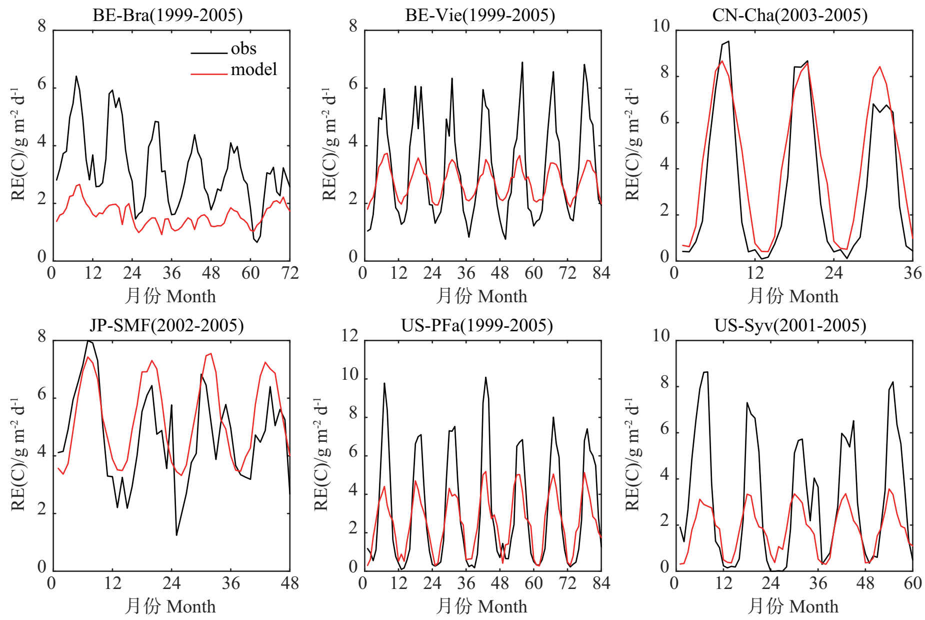


续附图1 Fig. S1 (Continued)

草地 Grasslands (GRA)

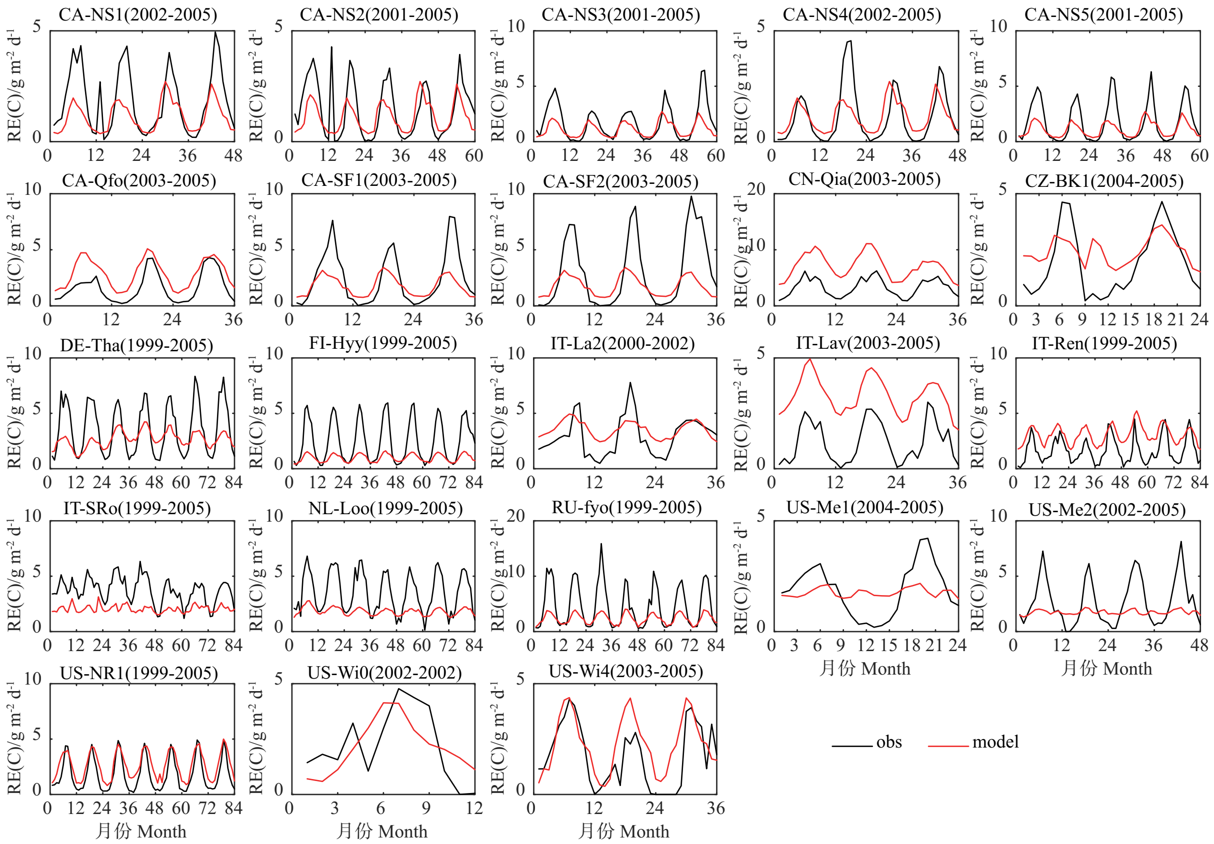


混交林 Mixed forest (MF)



续附图1 Fig. S1 (Continued)

常绿针叶林 Evergreen needleleaf forest (ENF)



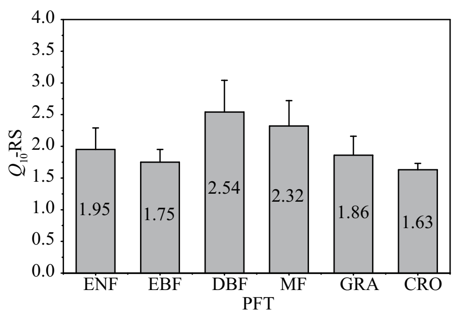
续附图1 Fig. S1 (Continued)

附表2 CLM模型呼吸作用参数对模拟结果的影响
Table S2 Effects of respiration of CLM model on simulation results

参数 Parameter	RS对各参数的敏感度系数 Sensitivity coefficient of RS to parameters (β-RS)	RA对各参数的敏感度系数 Sensitivity coefficient of RS to parameters (β-RA)	RE对各参数的敏感度系数 Sensitivity coefficient of RE to parameters (β-RE)
Q_{10}-RS	0.88	0.57	0.82
Q_{10}-RA	0.16	0.31	0.13
K	0.63	0.46	0.60
MR_{base}	0.19	0.35	0.15

Q_{10}-RS：土壤呼吸温度敏感性；Q_{10}-RA：自养呼吸温度敏感性；K：土壤碳库周转速率；MR_{base}：基础维持呼吸速率；β-RS = ΔRun/ΔP，ΔP为参数P的变化率（10%），ΔRun为参数P发生ΔP变化率时RS的相应变化率（%），β-RA和β-RE计算方法同β-RS.

Q_{10}-RS: The temperature sensitivity of soil respiration; Q_{10}-RA: The temperature sensitivity of autotrophic respiration; K: Turnover rate of the soil carbon pool; MR_{base}: The base rate of maintenance respiration; β-RS=ΔRun/ΔP, in which ΔP is the change rate of P, ΔRun is the corresponding change rate of RS as P changed, and the calculation of β-RA and β-RE are the same as β-RS.



附图2 各植被型Q_{10}-RS大小. PFT：植被功能型；Q_{10}-RS：土壤呼吸温度敏感性；MF：混交林；GRA：草地；ENF：常绿针叶林；EBF：常绿阔叶林；DBF：落叶阔叶林；CRO：农田.

Fig. S2 The size of Q_{10}-RS for all plant functional types. PFT: Plant functional type; Q_{10}-RS: The temperature sensitivity of soil respiration; MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland.